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ION BEAM MIXING IN MULTI-QUANTUM WELL STRUCTURES

FINAL TECHNICAL REPORT

BY

DR BERNARD L WEISS

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DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

UNIVERSITY OF SURREY

GUILDFORD, SURREY GU2 5XH, ENGLAND

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1. INTRODUCTION

The aims of the project were to investigate impurity induced disordering, using ion implantation, for the fabrication of optical waveguides in AlGaAs/GaAs quantum well structures.

Research prior to the initiation of the contract had indicated that the extent of the disordering, as measured by photoluminescence, was determined by both the nature, energy and dose of the implanted ion, and the temperature and time of the annealing process. While encouraging results were obtained for the loss characteristics of disorder delineated stripe optical waveguides, it was clear that not enough was known about the properties of the disordered QW structures to enable low loss disorder delineated stripe optical waveguides to be designed and fabricated in AlGaAs/GaAs MQW structures. In addition the impurity chosen to disorder the QW was also of importance and a detailed evaluation of the appropriate ion suggested that some of the less common impurities would probably be more suitable for photonic devices.

Consideration of the results discussed above led to a modification of the project program to include a detailed evaluation of the optical parameters and characteristics (spectral absorption coefficient and refractive index) of quantum well structures as a function of the shape of their confinement profile, i.e. the extent of the disordering, and the effect of an applied electric field, as these parameters are required for the design of waveguides and other signal processing devices. This study was carried out in parallel with an investigation of the disordering of AlGaAs/GaAs and InGaAs/InP QW structures with special reference to its application to the fabrication of disorder delineated stripe optical waveguides in InGaAs/InP QW structures.

2. PROGRESS

2.1 Modelling the optical Properties of Non-Square Quantum Wells

The model developed so far for the determination of the optical properties (absorption coefficient and refractive index) of single QW structures with and without an applied field in lattice matched and strain layer structures as a function of the shape of the non-linear QW confinement profile resulting from disordering of the QW, in that it includes the following effects in AlGaAs/GaAs (lattice matched) and InGaAs/GaAs (strained) QW structures:

i. hyperbolic shaped QW with an analytical solution,

ii. error function shaped QW well with a numerical solution,

iii. effective mass variations in the z (growth) direction,

iv. strain variation along the z (growth) direction,

v. non-parabolic mass and energy variations,

vi. valence band mixing,

vii. calculation of the continuum states just above the top of the QW,

viii. uniform applied electric field,

ix. 1S excitons,

x. all transitions are included in the calculations, including the "forbidden" ones,

xi. intersubband transitions including effects of the intensity of the incident radiation,

xii. spectral absorption coefficient for the TE and TM polarizations,

xiii. spectral refractive index for the TE and TM polarisations,

xiv. effect of applied electric field on the absorption coefficient and refractive index for TE and TM polarisations.

The results obtained so far using this model have demonstrated that[1-19]:

i. the hyperbolic function may be used to model the confinement profile of a disordered QW, except for the very early stages of interdiffusion. The results produced by this model has been shown to be correct by comparison with those produced by an error function profile which is in fact more precise but suffers from the problem of not being able to be solved analytically with the inevitable burden of numerical computation[1],

ii. the selection rules for the bound state transitions are relaxed for non-square QWs and lead to modified optical properties[2,3],

iii. during interdiffusion additional bound states are pulled into the top of the QW from the continuum above and, under certain conditions, these states may produce significant changes in the optical properties of the QW structure, which affect the design and operation of devices[3],

iv. the absorption coefficient and refractive index are both sensitive to the polarisation of the propagating optical wave and to the crystallographic orientation of the non-square QW structure[12,14,15,19],

v. disordering may be used to modify both the confinement profile and the energy shift due to the Quantum Confined Stark effect (QCSE) in such non-square QW structures. The effect of these changes is to modify the spectral absorption coefficient and the Stark shift for a given applied voltage: it may be used to reduce the voltage required to produce a given Stark shift[16-18],

vi. for the inter-subband transitions, disordering may be used to modify the spectral absorption curve of the QW structure over a very large wavelength range which is in excess of 8 μm to 40 μm, without any significant reduction in detection sensitivity[6],

vii. for strain layer structures, such as InGaAs/GaAs and disordered InGaAs/InP QW structures, the model has demonstrated the effect of disordering on the optical characteristics of QW structures[4,5,13]. In particular, for the interdiffusion of only group III atoms in InGaAs/InP, the

model shows that disordering of the as-grown lattice matched structure results in a strained QW structure. The confinement profile of this disordered QW structure contains two miniwells at the top of the as-grown square QW structure, which contain bound states and the well width remains that of the as-grown well regardless of the extent of the disordering process. Thus the optical properties of this disordered structure are modified and give rise to some interesting device possibilities[7].

2.2 Implantation induced disordering of AlGaAs/GaAs QW structures

The fabrication of disorder delineated stripe optical waveguides in AlGaAs/GaAs structures requires the disordering process to produce enhanced interdiffusion across the well/barrier interface without increasing the free carrier level or any recombination centres in the structure which could give rise to additional absorption. In this study single quantum well structures were studied to simplify the analysis of the experimental results and to enable the QW model to be applied to these experiments.

The results show that:

i. the use of low dose low energy oxygen implantation (i.e. 5×10^{13} O^+ @ 155 keV) produces a very large bandedge shift, as measured by photoluminescence (PL), for a given annealing temperature and time[20].

ii. the doping effect of the implanted oxygen appears to reduce the intensity of the PL emission with increasing ion dose and annealing temperature and time. This is thought to be due to the implanted oxygen removing free carriers which has been observed previously for oxygen doped AlGaAs. Consequently, using implanted oxygen to disorder QW structures would result in the use of the lowest annealing temperature and time together with the removal of free carriers

thereby reducing the free carrier loss. This also demonstrates that the electrical activity of the disordered structure may be varied at the same time.

iii. aluminium implantation was also thought to produce enhanced disordering, although in comparison to oxygen implantation, the extent of the disordering as measured by PL was much less than that due to oxygen under the same conditions, although it is a host lattice ion it was not expected to introduce any additional carriers[21].

2.3 Properties of Disorder Delineated Stripe Optical Waveguides

Disorder delineated stripe optical waveguides in InGaAs/InP QW structures were investigated here together with the computer modelling of the propagation characteristics of waveguides with non-square refractive index variations across the guiding layer[25]. The implantation of P into InGaAs/InP produced significant QW disordering which was used to fabricate low loss disorder delineated stripe optical waveguides[22-24].

2.4 Deuterium passivation of acceptors in Si doped p-type GaAs for optical waveguide fabrication

The exposure of bulk GaAs to a deuterium plasma at low temperatures results in the passivation of carriers in the bulk Si doped p-type GaAs material. This reduced carrier level results in an increased material refractive index thereby forming a planar optical waveguide. The results[26-29] show that:

i. the thickness of the passivated layer is a function of the sample temperature during plasma exposure,

ii. the passivation of the carriers in the bulk material, as determined by SIMS profiles of the deuterium and the refractive index changes used to calculate the change of refractive index,

iii. the waveguide modal analysis agreed with the refractive index changes calculated from the change of carrier concentration,

iv. the results presented demonstrate the feasibility of producing waveguides in GaAs by deuterium passivation of acceptors in GaAs.

3. CONCLUSIONS

The work carried out under this contract has demonstrated theoretically the feasibility of using QW disordering for the controlled modification of the optical properties of single QW structures, in particular the absorption coefficient and the refractive index. In addition, the effects of an applied electric field on both the bandedge shift and the consequential change in absorption coefficient, have also been determined as they are of considerable importance for the design of high speed signal processing devices, such as modulators based on the Quantum confined Stark Effect.

Low dose low energy oxygen implantation into AlGaAs/GaAs QW structures was found to produce very significant QW disordering, in fact greater than that produced by any other ion for the same process parameters. Since this process is thought to reduce the free carrier concentration at the same time as disordering the quantum well it looks very attractive for the fabrication of optical waveguides. On the other hand implanted aluminium ions were found to disorder AlGaAs/GaAs QW structures, although the extent of the disordering was much less than that for oxygen for the same process parameters. Host lattice implantation, i.e. phosphorous into InGaAs/Inp was found to produce significant disordering which was used to produce low loss disorder delineated stripe optical waveguides.

4. SUGGESTIONS FOR FURTHER WORK

The research described in this report demonstrates that the properties of as-grown and disordered QW structures in both lattice matched and strain layer material systems can be predicted although the above model only considers single quantum well structures. Clearly for the model to be applicable to guided wave optical devices it must be extended to include multiple quantum well (MQW) structures. The results already obtained for the QCSE in disordered structures indicates that device losses and switching voltages may be reduced by careful modification of the QW confinement profile which may be achieved using disordering. Consequently, it is proposed that the next stage of the work is concerned predominantly with the use of disordering for the optimisation of the properties of devices based on disordered QW structures and the control and characterisation of the disordering process. This proposed work will form the basis of the application for the extension of this work.

5. PUBLICATIONS ARISING OUT OF THE RESEARCH COVERED BY THIS CONTRACT

A. Modelling the Optical Properties of Quantum Well Structures

1. E H Li and B L Weiss, "The optical characteristics of AlGaAs/GaAs hyperbolic quantum well structures", J Appl Phys 70, 1054-1056, 1991.
2. E H Li and B L Weiss, "The change in refractive index of AlGaAs/GaAs single quantum wells due to impurity-induced mixing", IEEE Photon Technol Lett 3, 787-790, 1991.
3. E H Li and B L Weiss, "The dielectric properties of non-square AlGaAs/GaAs single quantum wells at photon energies below the bandgap", Appl Phys Lett 59, 3312-3314, 1991.

4. E H Li, J Micallef and B L Weiss, "Confinement subbands in an InGaAs/GaAs non-square quantum well", Japan J Appl Phys 31, L7-L10, 1992.

5. J Micallef, E H Li and B L Weiss, "Polarization dependent interband optical absorption in a strained non-square InGaAs/GaAs quantum well", Electron Lett 28, 526-528, 1992.

6. E H Li, B L Weiss and A Laszcz, "Linear and non-linear intersubband optical absorption in a diffusion induced AlGaAs/GaAs quantum well at far IR wavelengths", Electron Lett 28, 885-886, 1992.

7. E H Li, J Micallef and B L Weiss, "Confinement and strain profiles produced by cation interdiffusion in $In_{0.53}Ga_{0.47}As/InP$ quantum wells", Appl Phys Lett 61, 435-437, 1992.

8. E H Li and B L Weiss, "Exciton optical absorption in a diffusion induced non-square AlGaAs/GaAs quantum well", SPIE Symposium on Compound Semiconductor Physics and Devices, Conference on Quantum well and Superlattice Physics, 23-27 March 1992 Somerset, NJ, USA.

9. E H Li, J Micallef and B L Weiss, "Subband states and optical properties of a strained non-square quantum well", SPIE Symposium on Compound Semiconductor Physics and Devices, Conference on Quantum well and Superlattice Physics, 23-27 March 1992 Somerset, NJ, USA.

10. E H Li and B L Weiss, "Analytical solution of the subbands and absorption coefficients of AlGaAs/GaAs hyperbolic quantum wells", IEEE Quantum Electron - accepted for publication.

11. E H Li, B L Weiss and K S Chan, "Effect of interdiffusion on the subbands in an $Al_xGa_{1-x}As/GaAs$ single quantum well structure", Phys Rev B - accepted for publication.

12. E H Li and B L Weiss, "The effect of well shape on the refractive index of AlGaAs/GaAs single quantum well structures", Optical and Quantum Electron - submitted for publication.

13. J Micallef, E H Li and B L Weiss, "The effects of strain on the confinement profile of disordered InGaAs/GaAs single quantum wells", Superlattices and Microstructures - accepted for publication.

14. E H Li, B L Weiss, K S Chan and J Micallef, "The polarisation dependent refractive index of an interdiffusion induced AlGaAs/GaAs quantum well", Appl Phys Lett - submitted

15. E H Li and B L Weiss, "The birefringence of disordered AlGaAs/GaAs quantum well structure", Electron Lett 28, 2114-2115, 1992.

16. E H Li, B L Weiss and J Micallef, "The quantum confined Stark effect in an interdiffused AlGaAs/GaAs quantum well", Appl Phys Lett - submitted for publication.

17. E H Li and B L Weiss,"Enhanced electroabsorption in disordered AlGaAs/GaAs quantum wells", IEEE Photon Technol Lett - submitted for publication.

18. E H Li, B L Weiss and K S Chan, "The electro-optic effect in non-square quantum wells", in preparation.

19. E H Li and B L Weiss, "The refractive index of QW structures for incident light normal to the quantum well growth direction", in preparation.

B. Implantation Induced Quantum Well Disordering

20. I V Bradley, B L Weiss and J S Roberts, "Aluminium implantation induced disordering of GaAlAs/GaAs quantum well structures for optoelectronic applications", Special issue of Optical and Quantum Electronics on MQW Mixing for Optoelectronic Applications, 23, S823-S828, 1991.

21. B L Weiss, I V Bradley, N J Whitehead and J S Roberts, "Oxygen implantation induced disordering of AlGaAs/GaAs quantum well structures", J Appl Phys 71, 5715-5717, 1992.

C. Disorder Delineated Stripe Optical Waveguides in InGaAs/InP QW Structures using Phosphorous Implantation

22. N J Whitehead, W P Gillin, I V Bradley and B L Weiss, "Disordering of InGaAs-InP QWs by P implantation", IEE Colloquium on Applications of QWs in Optoelectronics, June 1990.

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25. B L Weiss and A P Zhao, "The influence of well shape on the propagation characteristics of planar MQW waveguides", IEEE Photon Technol Lett 2, 801-3, 1990.

D. Properties of Waveguides Produced by Carrier Removal

26. J M Zavada, B L Weiss, I V Bradley, B Theys, J Chevallier, R Rahbi, R Ardinall, R C Newman and H A Jenkinson, "Optical waveguides formed by deuterium passivation of acceptors in Si doped p-type GaAs epilayers", J Appl Phys 71, 4151-4155, 1992

27. J M Zavada, B L Weiss and B Theys, "Deuterium plasma reduction of free carrier level in GaAs for optical waveguides", OSA Annual Meeting, Boston, USA, November 4-9, 1990.

28. J M Zavada, B L Weiss, I V Bradley, B Theys, J Chevallier, R Rahbi, R C Newman, R Ardinal and H A Jenkinson, "Optical waveguides formed by hydrogen passivation of dopant atoms in p-GaAs:Si epilayers", European Mat Res Soc, 26-30 November 1990.

29. J M Zavada, B L Weiss, I V Bradley, B Theys, J Chevallier, R Rahbi, R C Newman, R Ardinall, H A Jenkinson, "Optical waveguides formed by deuterium plasma passivation of acceptors in Si doped p-type GaAs epilayers", Materials Science and Engineering B9, 379-382, 1991.